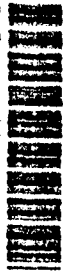


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TR-93(3478)-1

## Investigation of ACC/CCI Tunnel Diodes

1 November 1993

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This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.



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are identical to the DMSP devices, and the laboratory findings were the same. The NASA diodes exhibit the same problems with respect to workmanship found in the DMSP components. Because of this commonality, the evaluation of the NASA devices is included in this report. The NASA diodes were manufactured before the changes implemented for the DMSP components, and, based on the available evidence, we suggest that their reliability should not be assumed.

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## **I. INTRODUCTION**

In October of 1991, a DMSP radio-frequency detector in channel T2 of system B6 failed during testing. The detector module exhibited low output. Subsequent investigation initiated by Aerojet, the DMSP prime contractor, traced the problem to the tunnel diode in the detector. Tunnel diodes are used in a number of low-power microwave applications. The tunnel diodes are manufactured by Custom Control Components (CCI), and the detector modules by Advanced Control Components (ACC). Although ACC and CCI are separate companies "on paper," they share the same manufacturing facility and are not readily distinguishable by the casual observer. Destructive physical analyses carried out after the failure indicated that contaminants had been introduced during fabrication. Site visits at ACC/CCI by contractor and Aerospace personnel led to a general improvement of the manufacturing process with a concomitant improvement in detector reliability. A review of the available literature pointed to a tunnel-diode failure mechanism found some years ago by researchers at Comsat and led to a recommendation of an additional component screen that has now been proven effective in improving tunnel-diode reliability.

In the summer of 1993, ACC/CCI tunnel diode issues again arose when NASA inquired about Aerospace's experience because of failures encountered on the AMSU/A program.

This document summarizes the work carried out at The Aerospace Corporation by the DMSP program office and by the Electronics Technology Center/Technology Operations in connection with the SSM/T2 B6 failure. The results of the analysis of tunnel diodes for NASA are also presented. Because the background material, the analysis procedures, and the results obtained are so similar, it seems sensible to include all of the tunnel-diode results in a single report.



## II. BACKGROUND

### A. TUNNEL DIODE OPERATION

The tunnel diode was first described by L. Esaki in 1958.<sup>1</sup> A quite complete description of tunnel diodes may be found in the standard reference book by Sze.<sup>2</sup> A very brief discussion of tunnel-diode operation (drawing heavily on ref. 2) is included as an appendix as an aid to an understanding of their degradation.

A sketch showing the current/voltage characteristic of the diodes in question is shown in Figure 1. In the DMSP detector application of concern here, the diodes are not operated in the negative-resistance region but near zero bias where their non-linear I-V characteristic suits them for use as microwave detectors.

### B. TUNNEL DIODE FABRICATION

The ACC/CCI tunnel-diode technology is about 25 years old. Workers at Comsat Corporation published a review of these "ball alloy" diodes some years ago.<sup>3</sup> The present construction is identical and is illustrated in Figure 2. An arsenic-doped nickel pellet is placed on a germanium die and alloyed to the die by heating. A tin-plated nickel mesh "ribbon" is then attached to the pellet. The die is etched, leaving a relatively massive chunk of nickel perched atop a thin stalk of germanium (usually called the "mesa"). The germanium is a heavily doped n-type material (highly doped n-type material is referred to as " $n^+$ "). Tin from the metal pellet diffuses into the

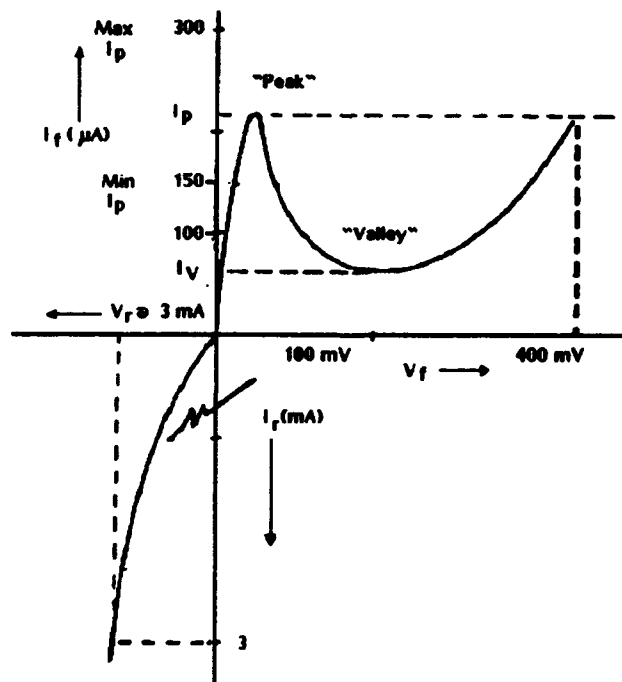


Figure 1. Tunnel diode I-V characteristics.

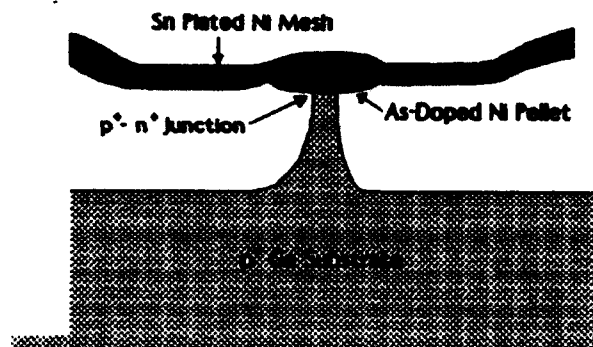


Figure 2. The ball alloy tunnel diode in cross section.

germanium, resulting in a heavily doped p-type ( $p^+$ ) region at the top of the stalk, and a " $p^+ - n^+$ " diode junction is thus formed. The ball alloy configuration results in a device with minimum area and thus minimum junction capacitance, a primary concern in the microwave application of tunnel diodes.

The germanium die is mounted in a U-shaped alumina block, as indicated in Figure 3, using gold-tin solder as a die attach. The ribbon, which contacts the pellet at the top of the die, is captured by two "posts" formed by piling up an insulating epoxy resin. One end of the ribbon is attached by conductive silver epoxy to a gold pad on top of one leg of the alumina channel to form the top diode contact. The other diode contact is made through the die via gold plating on the alumina block. An electron micrograph of tunnel-diode assembly is shown in Figure 4 (compare with the sketch of Figure 3).

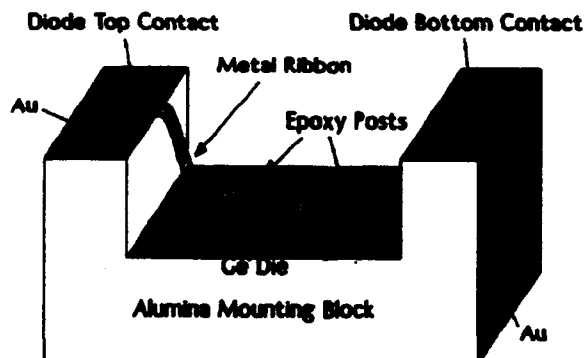


Figure 3. The diode mounted in the alumina block.

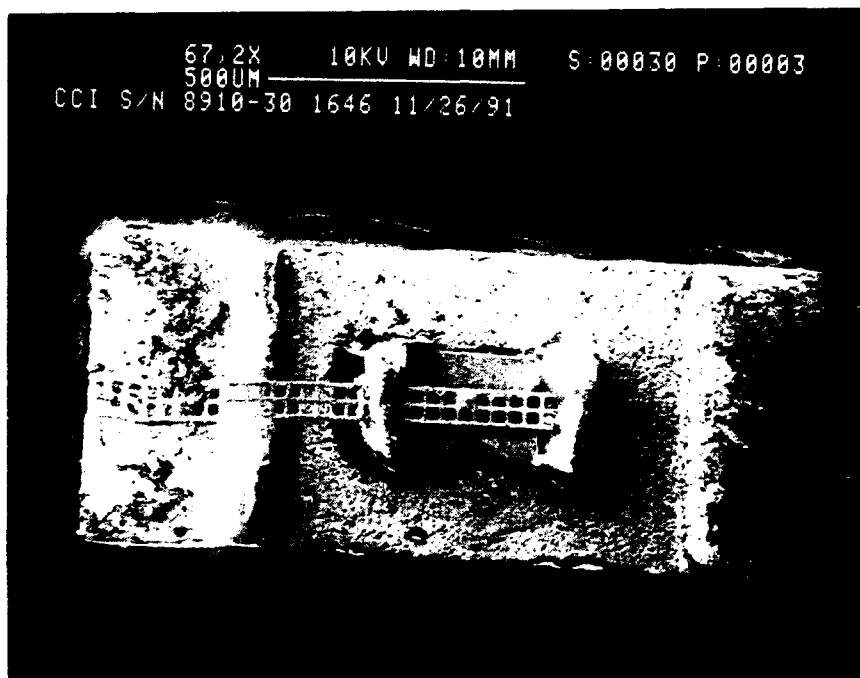


Figure 4. Electron micrograph showing the complete diode assembly (DSMP device, LDC 8910, S/N 30, 67 $\times$  magnification).

The tunnel-diode assembly (Figures 3 and 4) is the key component in the detector modules, but it is not the only component. The diode assembly is mounted with several other components on a small circuit board and sealed in a cylindrical tube. The sealed tube is 0.515 in. long and 0.187 in. in diameter. The tube is incorporated in yet another structure containing RF connectors. Because this report is concerned primarily with anomalies associated with the tunnel diodes themselves, these other parts of the detector will not be discussed further.

### C. TUNNEL DIODE DEGRADATION

Ball alloy tunnel diodes are known to degrade by a mechanism involving mechanical stress in the thin mesa region.<sup>4</sup> Stress can easily be built in during construction when the ribbon is attached to the alloy contact perched atop the narrow germanium stalk. Some diodes may happen to be highly stressed during fabrication, while others are not. The stress is relieved by the generation of defects in the germanium. These defects in turn give rise to electron states in the junction area that lie in the forbidden gap. Electrons can cross the junction by transitions involving these states as well as by tunneling completely across the gap, and the valley current of the diode, therefore, increases.

A thermal screen was proven effective for the improvement of diode reliability by the elimination of those diodes prone to early failure because of the deleterious effects of mechanical stress.<sup>5</sup> Heating accelerates the annealing of the germanium and the generation of defects. The authors of the Comsat study developed a screening procedure in which diodes were heated at 140°C for 1 h. Diodes that exhibited a change greater than 10% in either the peak or the valley current were rejected.

### III. DESTRUCTIVE PHYSICAL ANALYSIS

The diodes were examined using either a Leica/Cambridge Stereoscan 200 scanning electron microscope (SEM) equipped with a Tracor TN5500 energy dispersive X-ray analyzer for elemental analysis or a Stereoscan 250 instrument. Stereoscopic images were found to be particularly effective in revealing various features of interest. Stereographic imaging is accomplished with a SEM by taking two pictures with the specimen tilted at different angles. A stereoscopic viewer is then used to combine the two images into a stereomicrograph. Note that a great many electron micrographs of the tunnel diodes, including quite a number of stereo pairs, were obtained and are available for examination.

Unless otherwise stated, the term "epoxy" in the following discussion refers to the insulating epoxy used in the fabrication of the diode structure proper.

#### A. DMSP DIODES

Destructive physical analysis of DMSP diodes was first undertaken by Hi-Rel Laboratories, Inc., then located in Monrovia, Calif., at the request of Aerojet. Aerojet and Aerospace personnel were on hand during most of this work. Hi-Rel deprocessed the failed device [lot date code (LDC) 8910, S/N 30] and carried out both optical and electron microscope examination and electrical characterization.

The DMSP failed device, LDC 8910, serial number 30, was subsequently brought to Aerospace. In ACC/CCI internal company nomenclature, this device is termed "type MM2." This device had been installed in a detector module. Hi-Rel Laboratories had deprocessed the module and removed the diode assembly. During a trip to ACC/CCI, two other MM2 diodes, still installed in detector modules, were obtained. In addition, ten diode assemblies of type "MM6" were also received for evaluation. Not all of these devices were examined, however. The investigation at Aerospace was undertaken in order to take a further look at the tunnel diodes complementary and supplementary to the Aerojet/Hi-Rel analysis. Most of the results reported in this section were obtained on device LDC 8910, S/N 30.

The germanium die appeared to have sustained some damage during fabrication, possibly as a result of rough handling with tweezers. One side of the die does not have a straight edge, but instead shows a deep indentation (Figure 5). The indented region does not have sharp edges, and indeed subsequent etching by potassium hydroxide could well have smoothed any projections. The critical mesa region is well away from the indentation, and the condition of the die along the edges shouldn't affect performance.

The integrity of the die attach is open to question. Cavities are visible beneath the germanium. Gold/tin solder is essentially visible only as a blob located on one side of the die. The solder in the blob has a distinct texture, with ridges radiating from a point (Figure 6). The pattern might have been formed by sliding of the chip on melted solder or may be a splash pattern. This apparent splash pattern suggests that the solder may not have been hot enough to bond to the chip.

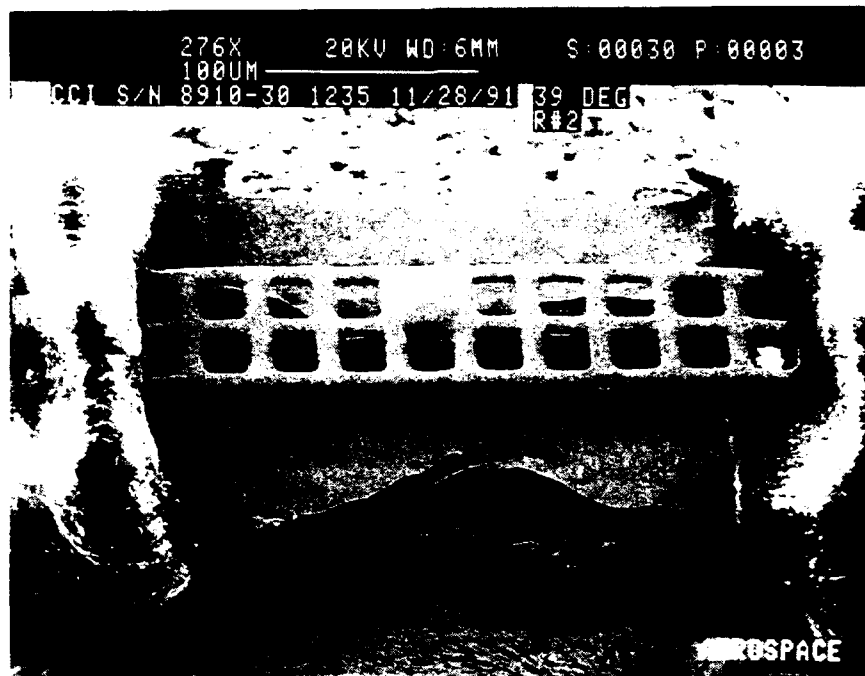


Figure 5. Overall appearance of the die (DMSP device, LDC 8910, S/N 30, 276 $\times$  magnification). The nearer side has apparently been chipped. The overexposed features at the edges of the image are the insulating epoxy posts, which are charging in the SEM beam. The contact ribbon runs between the posts near the center of the image. The diode mesa is beneath the filled mesh near image center.

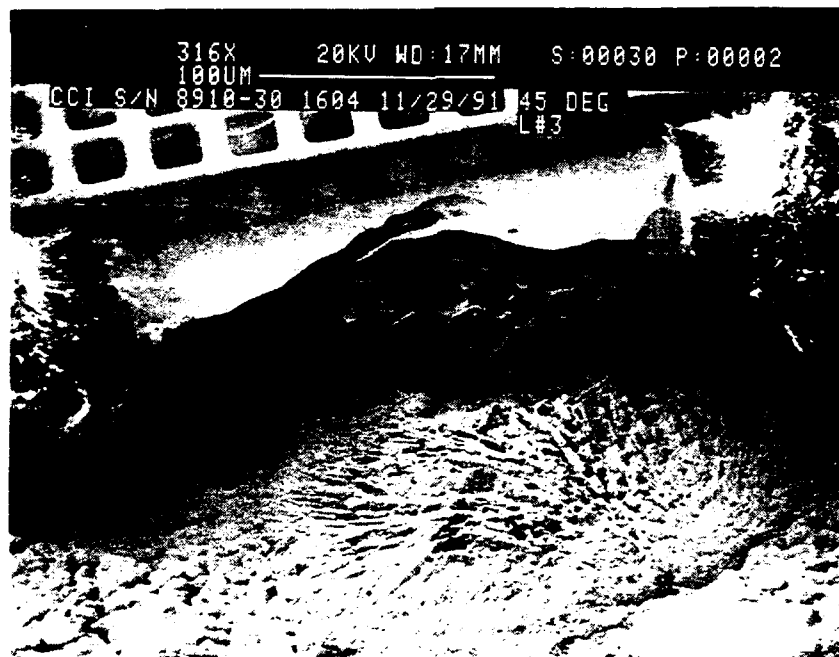


Figure 6. Higher magnification view of bottom right area of Fig. 5 (DSMP device, LDC 8910, S/N 30, 316 $\times$  magnification). The fan (or sea-shell) shaped region in the right foreground is the Au/Sn die attach. Optically, the silver-colored solder stands out clearly against the gold. The die may not be firmly soldered to the substrate.

Epoxy resin is smeared up over the edges of the die during fabrication. The epoxy secures the mesh ribbon to the contact posts, and the presence of some epoxy on the die is expected. After etching of the Ge, thin, tapering ridges of epoxy are left along the sides of the die adjacent to the posts (Figure 7). There is evidence that epoxy might have spread beneath the die (Figure 8). There is a thin strip of material, apparently epoxy, under the die. This material can be seen to join continuously with the epoxy posts. Epoxy beneath the die could degrade the electrical contact between the chip and the substrate. However, the epoxy might have spread only along an edge of the die and may not be a significant concern.

The most alarming observations are those showing excess epoxy resin on and under the mesh strap used to make electrical contact to the alloy ball. The electron micrograph of Figure 9 was obtained by tilting the specimen to view beneath the ribbon. The thin "mesa" is visible at the left. The lighter material near the right center of the image is residual epoxy resin on the bottom of the contact ribbon. Figure 10 shows a closer view of some "stringers" of epoxy that extend from the die to the ribbon. Steroscopic views are particularly graphic.

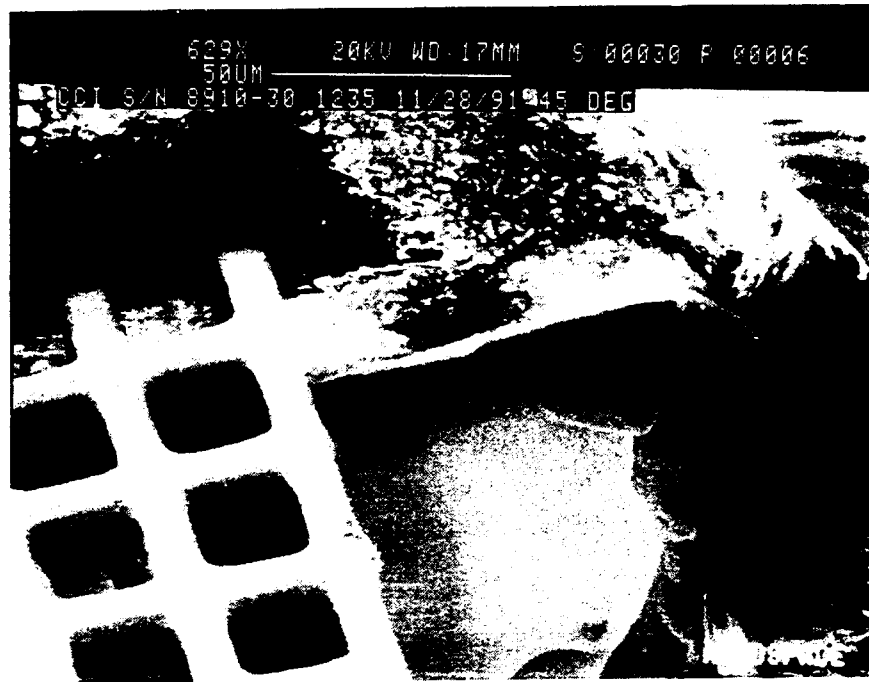


Figure 7. Epoxy post (top) is bright because of charging (DSMP device, LDC 8910, S/N 30, 629 $\times$  magnification). The contact ribbon is at the left, Ge die is in right foreground. Etching of Ge die has left a permanent shoulder of epoxy.



Figure 8. Bottom edge of die (DSMP device, LDC 8910, S/N 30, 444 $\times$  magnification). Gold substrate in foreground. A band of epoxy runs from the epoxy post at the left, along the bottom of the die. The epoxy mostly appears as a dark band, but a bright region (charging) can be seen toward the right.

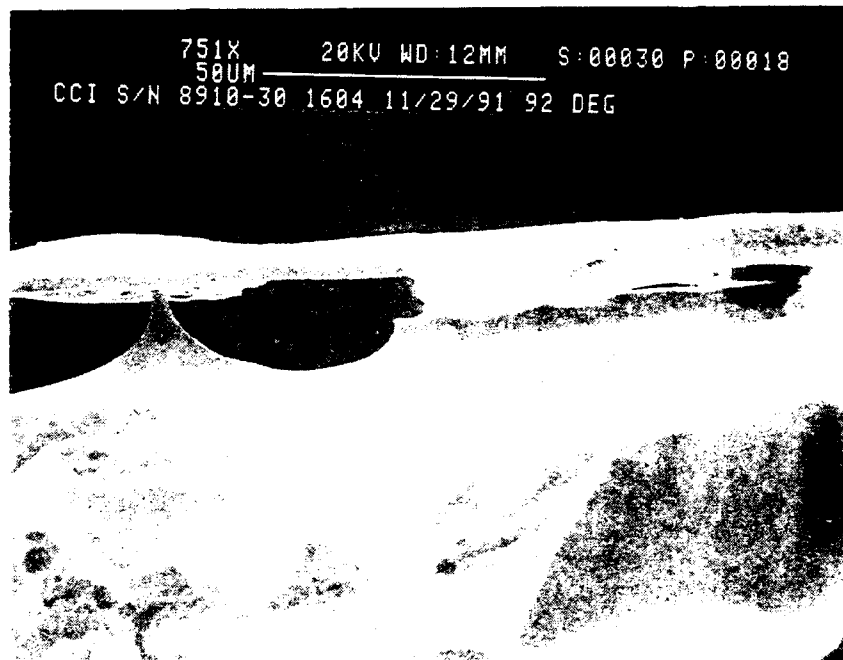


Figure 9. The bottom of the ribbon mesh (DSMP device, LDC 8910, S/N 30, 751 $\times$  magnification). The mesa is at the left. Epoxy contamination is visible (light area) toward the right.

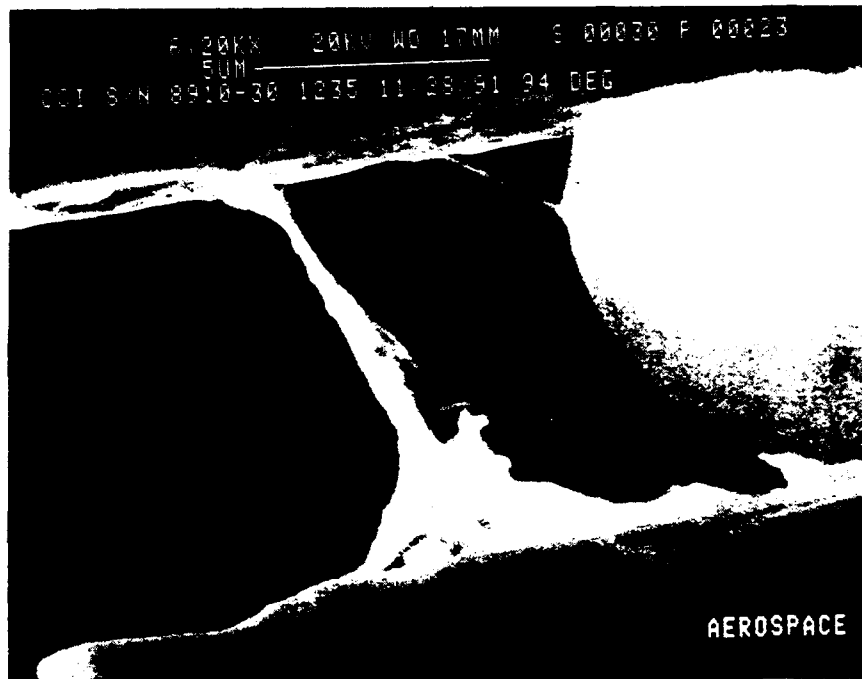


Figure 10. Closer view of epoxy contamination beneath ribbon mesh (DSMP device, LDC 8910, S/N 30, 6200× magnification). A "stringer" is at the center, a larger glob of epoxy with a small stringer at the right.

Two of the "MM6" DMSP diodes were examined in some detail. These devices appeared, in general, to be "cleaner" than the failed device (8910, S/N 30); however, some residual epoxy was evident beneath the ribbon.

## B. NASA DIODES

### 1. Procedures

The NASA diode packages were opened at Aerospace following a procedure initially worked out at Hi-Rel Laboratories. Two flats were ground on the sides of the cylindrical diode housing to form a "steeple" with its apex above the internal circuit board. The housing could be oriented by looking along the long axis through the glass end seals. The circuit board was then visible. The grinding was done by hand, starting with 280 grit emery paper. When the case was thinned sufficiently, two rectangular pieces of the case on opposite sides could be cut away with an X-ACTO knife, leaving only a ridge of material across the internal cavity that could be removed with small side cutters. The interior of the diode module was exposed at this stage of the process and could be inspected using optical or electron microscopy. The U-shaped assembly diode itself, described in Section II, mounted "face down" (i.e., "TT") with silver epoxy, could be removed by cutting away the epoxy in conjunction with a bit of (cautious) prying with the X-ACTO knife.

Five of the diode packages had been punctured to allow analysis of their internal atmospheres (the results will be summarized later). The small hole from this analysis was sealed with "two minute" epoxy prior to opening the case to preclude gross contamination of the package interior



by metal filings. The clear epoxy formed a small, neat plug well away from any regions of interest and will not be mentioned again.

An oxygen plasma etcher (the ubiquitous "Plasmod" model manufactured by Tegal Corp.) proved quite valuable in removing epoxy resin when needed. An oxygen plasma will selectively burn or "ash" organic compounds while not damaging other materials commonly found in microelectronic devices.

A focused ion beam (FIB) milling system (manufactured by FEI, Inc., Beaverton, OR; model 610) was useful in exposing the mesa region to obtain a better view. The FIB instrument employs a beam of gallium ions to mill away material from a specimen. Regions to be removed can be defined with submicron accuracy.<sup>6</sup>

## 2. Observations

The eight diodes examined are listed in Table I, together with a summary of the most important gas analysis information obtained by Pernicka Corp. (Fort Collins, CO). Gas analysis is performed by puncturing a device back in a vacuum chamber connected to a mass spectrometer. Very high values for water vapor, hydrocarbons, and other organic fluorocarbons are cited. These devices were all contaminated by epoxy resin on the ribbon and/or around the mesa.

Diode S/N 136 was received first. Mr. Bruce Sharp of Aerojet was at Aerospace during much of the work on this device. The diode assembly was actually still in the detector module with attached RF connectors. We verified that the device was electrically open using a Tektronix 576 curve tracer. After deprocessing the inner cylindrical diode assembly, we were subsequently able to check the I-V characteristics of the diode itself using a curve tracer and a Micromanipulator probe station. The diode was open.

The SEM revealed substantial epoxy resin contamination. Figure 11 shows diode S/N 136 as received. The dark mound in the center is the mesa region! Epoxy can also be seen on the bottom of the ribbon. An additional large glob of epoxy connecting the ribbon and the die is visible at the left. After "ashing" the device in the plasma etcher, the epoxy, while not completely removed after one hour, was considerably reduced in density. The mesa can be clearly discerned in the micrograph of Figure 12.

Table 1. List of NASA Diodes Analyzed

S/N	Vol. % H <sub>2</sub> O	Vol. % Hydrocarb.	Vol. % Fluorocarb.
108	6.4	1.0	1.8
113	N/A	N/A	N/A
115	N/A	N/A	N/A
136	N/A	N/A	N/A
142	53.0	5.9	6.7
157	19.4	0.9	0.0
167	7.1	0.7	0.4
172	8.0	0.6	0.0



Figure 11. As-received diode, looking under the ribbon (NASA device, S/N 136, 1200 $\times$  magnification). The dark mound in the center is the mesa. Another blob of epoxy is visible at the left of the image.



Figure 12. Higher magnification view of the mesa region of diode of Fig. 10 after 1 h of O<sub>2</sub> plasma etching (NASA device, S/N 136, 2930 $\times$  magnification). The mesa is visible through remnants of epoxy.

Figures 13 to 19 show general views of the NASA diodes and give some idea of the extent of contamination. A view of the top of the die and the ribbon at about a 45° angle and a view of the pinnacle area looking nearly parallel to the die surface are shown for S/Ns 113, 115, 142, 157, and 172. Specimen charging interfered with the low-angle view of diode S/N 108, but a higher magnification view of the top of the ribbon above the pinnacle has been provided, which clearly shows epoxy "stringers" (Figure 13b). Diodes S/N 113 and 115 were received in a separate shipment and were said to represent "cleaner" parts. In general, they were not as heavily contaminated, but still showed clear traces of epoxy contaminant (Figures 14a,b, 15a,b). Diode S/N 113 has an epoxy-covered mesa.

Diode S/N 167 (Figures 16a,b) was the most severely contaminated device in the group. The die was covered by splashes of epoxy. The ribbon almost appears to have been dipped in epoxy! The oxygen plasma "asher" removed much of the contaminant and exposed the mesa. Epoxy is visible on the ribbon of S/N 157 (Figures 17a,b), although the pinnacle is not obviously covered by epoxy. Diode S/N 172 (Figures 18 a,b) has epoxy contamination on the ribbon and on the die, including the mesa region.

Diode S/N 142 is a particularly interesting case. The mesa of this diode, as received, was covered by epoxy. There was no sign of the graceful, tapering "stalk" that we have come to expect in tunnel diodes (Figures 19a,b). The device was etched in an oxygen plasma, and the epoxy removed — still with no obvious mesa. The Ge appears to have fractured. The ribbon appeared to have been "mashed down" along one edge, and it seemed that the view of the mesa might simply have been blocked by the ribbon. Using the FIB, the ribbon was cut away to better expose the mesa region (Figures 20a,b); still, no "stalk" could be seen. The other side of the ribbon was also cut away, and, again, a tapering stalk was not evident (Figures 21a,b).

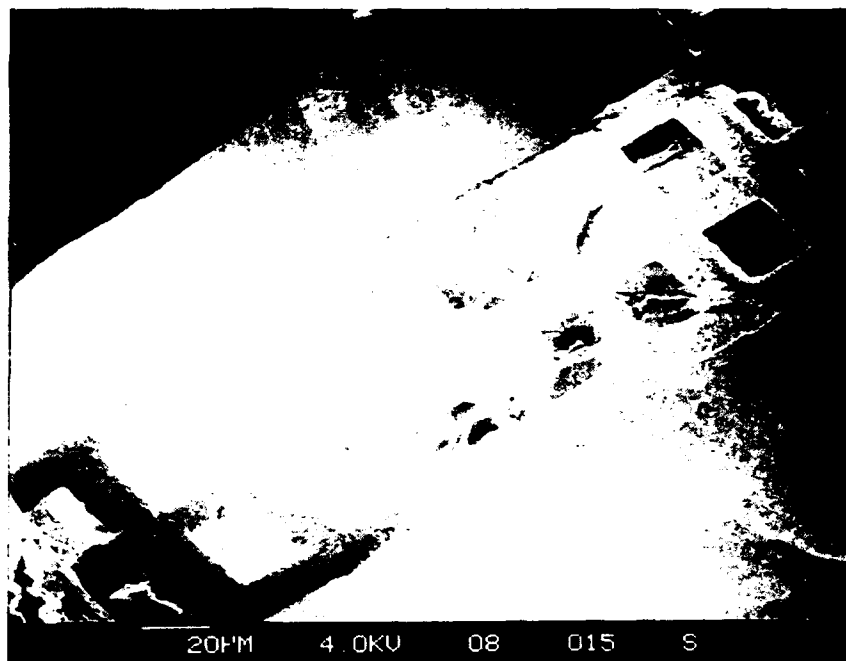


Figure 13a. Electron micrograph showing contamination of ribbon (NASA device, S/N 108, 475 $\times$  magnification). Epoxy stringers are evident in center holes in ribbon mesh.

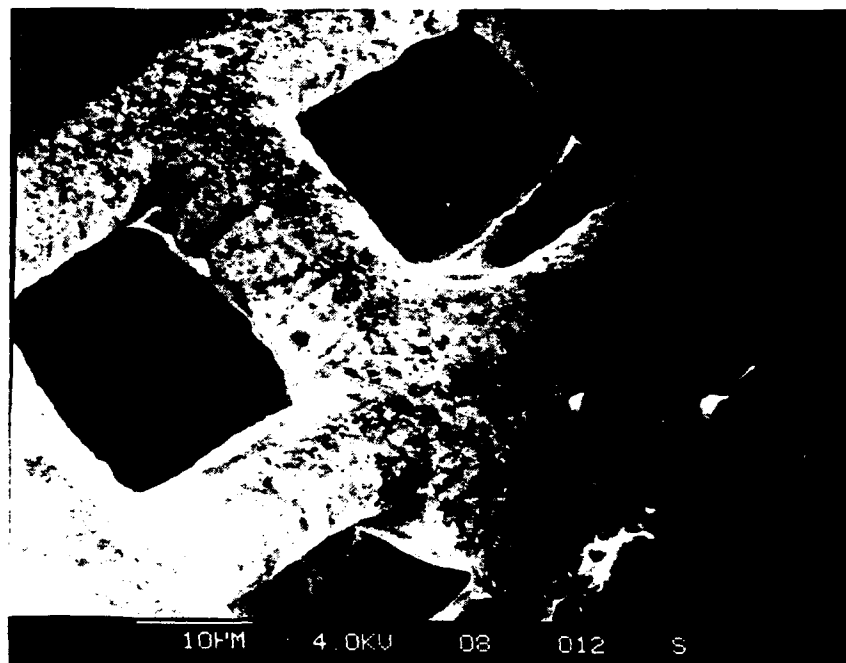


Figure 13b. Electron micrograph showing ribbon at higher magnification showing epoxy stringers more clearly (NASA device, S/N 108, 650 $\times$  magnification).

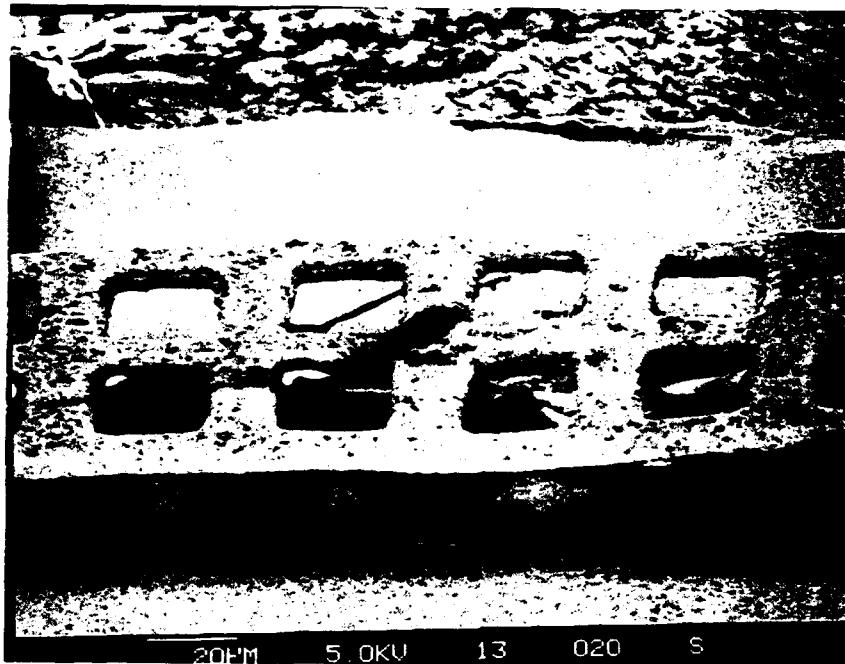


Figure 14a. Epoxy contamination appears as both dark areas on top of mesh ribbon and as bright areas (because of effects of charging) on sides and beneath ribbon (NASA device, S/N 113, 600 $\times$  magnification).

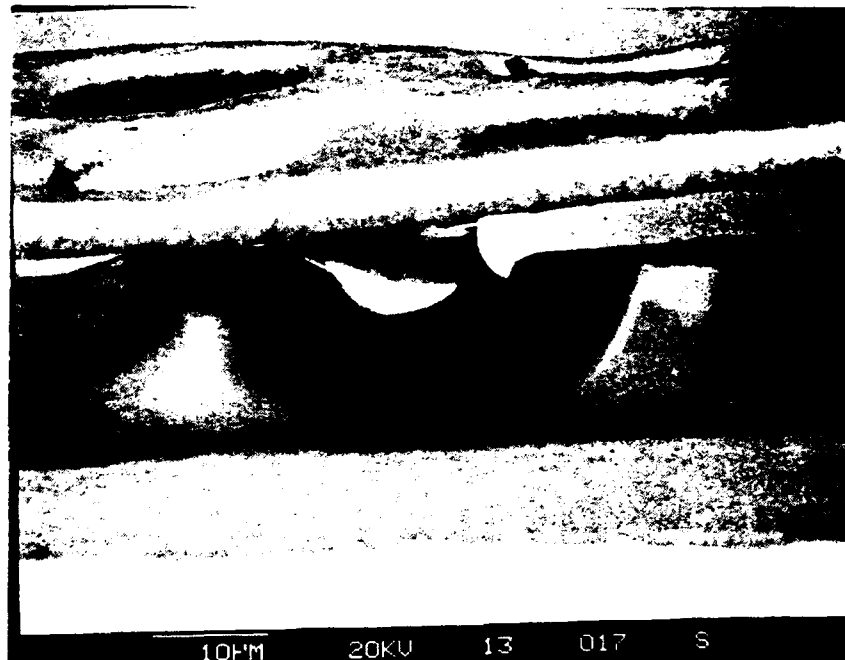


Figure 14b. Epoxy contamination around mesa (NASA device, S/N 113, 1600 $\times$  magnification). Note that the characteristic sharp edges associated with Ge appear rounded because of epoxy coating. Bright area at center is epoxy charging under beam.

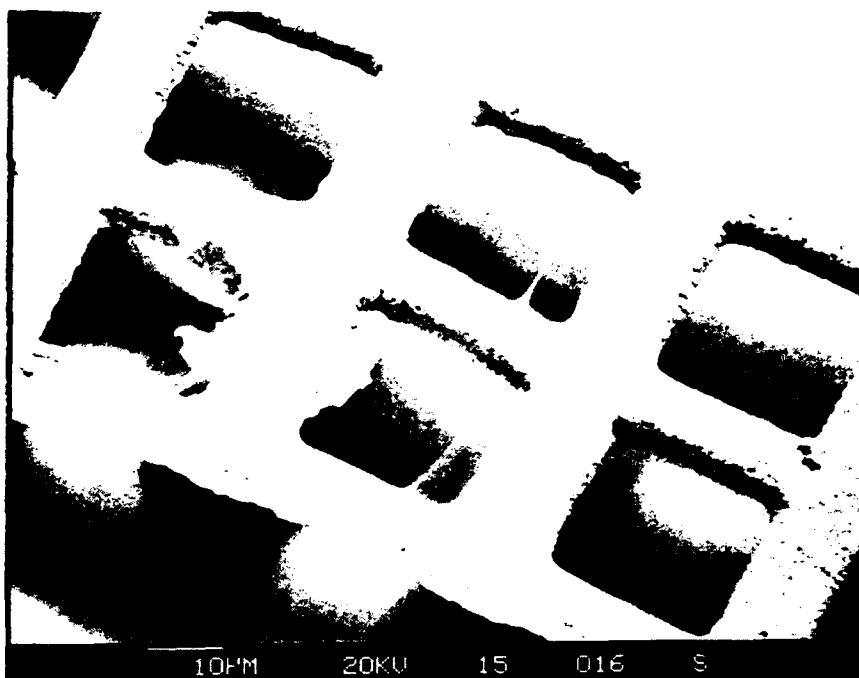


Figure 15a. Epoxy contamination. Note stringers in mesh openings near center of image (NASA device, S/N 115, 1100 $\times$  magnification).

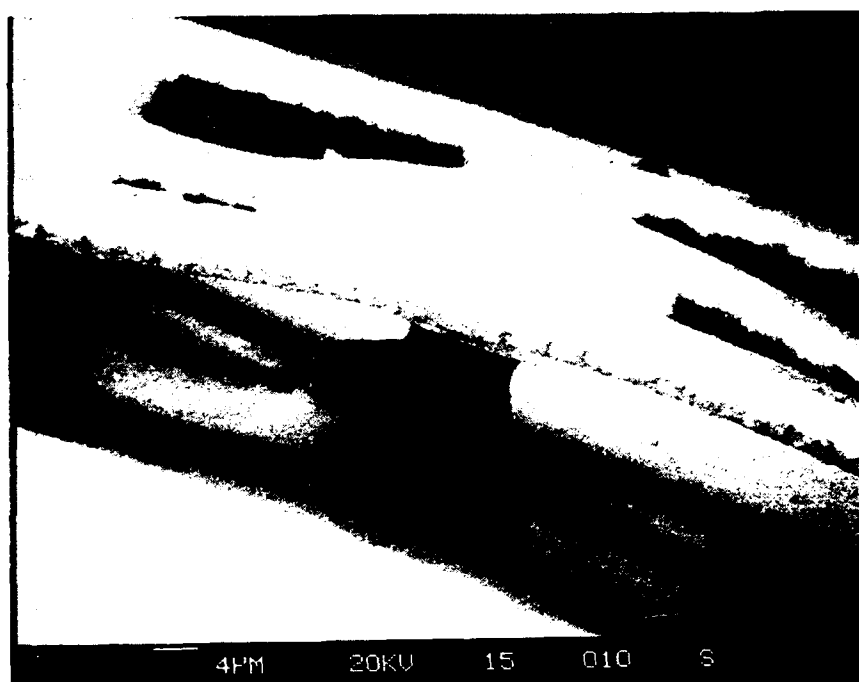


Figure 15b. Mesa in this device is not contaminated (NASA device, S/N 115, 1750 $\times$  magnification).

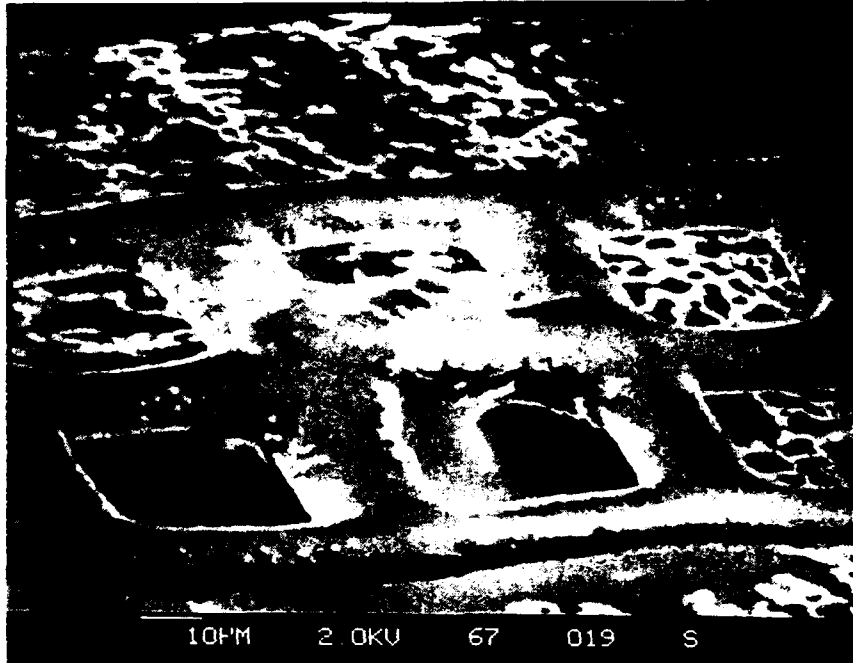


Figure 16a. This device is the most heavily contaminated of the NASA diodes (NASA device, S/N 167, 950× magnification). Note patches of epoxy on die. Ribbon actually appears to have been dipped in epoxy.

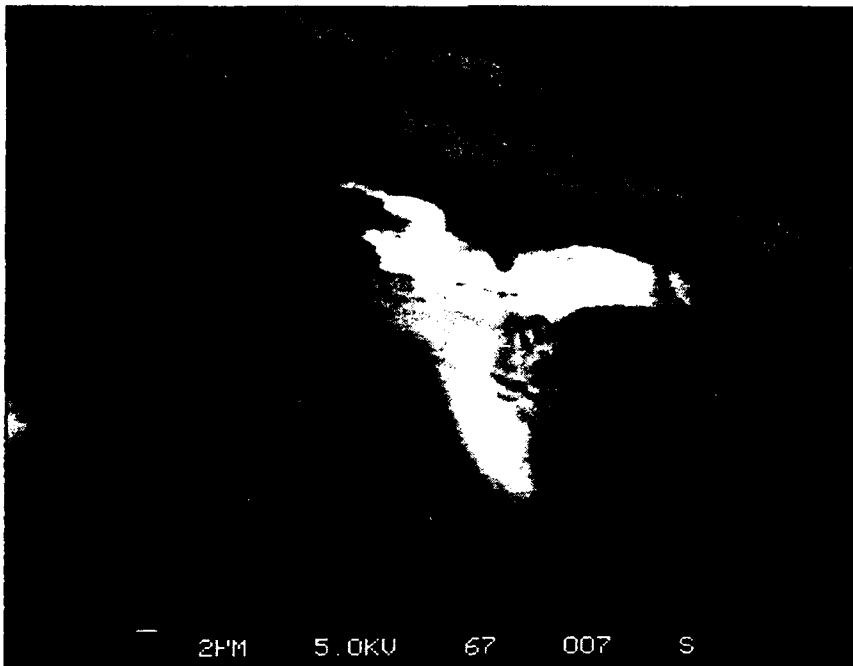


Figure 16b. Note complete coating of the mesa by epoxy (NASA device, S/N 167, 1000× magnification).

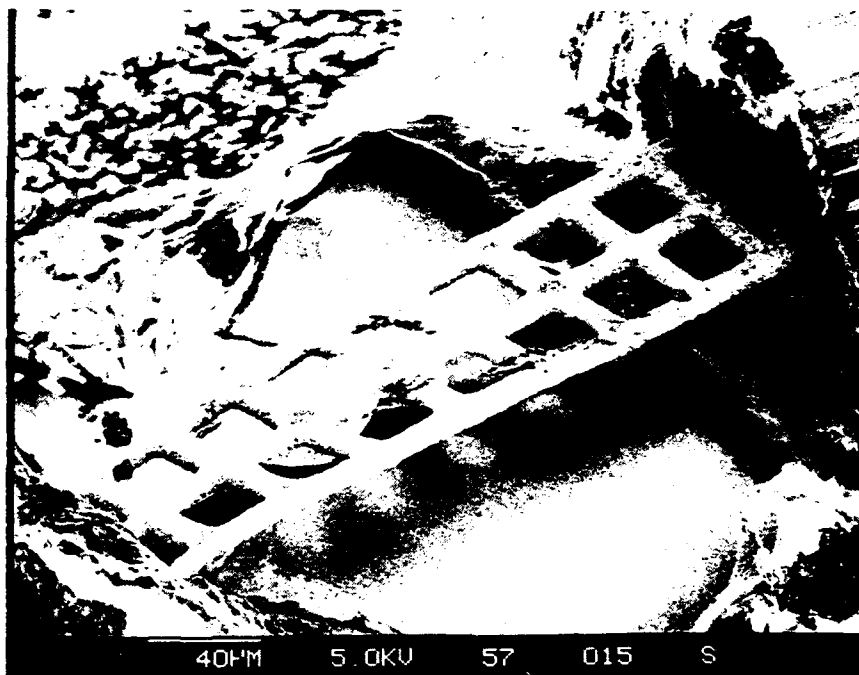


Figure 17a. Some epoxy contamination is evident on the ribbon (darker areas) (NASA device, S/N 157, 400× magnification).

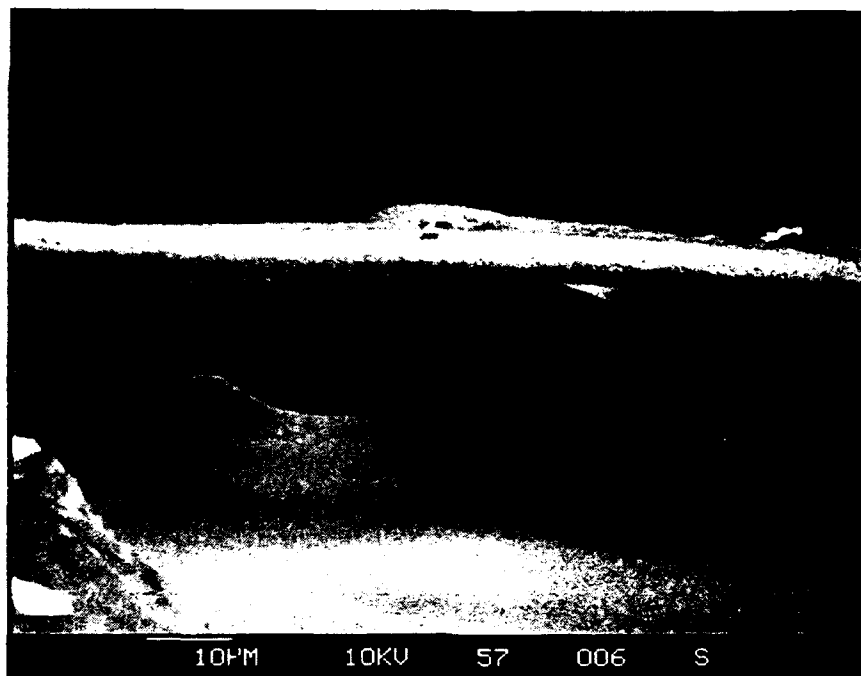


Figure 17b. The mesa in this device is not covered by epoxy, but epoxy is visible beneath the ribbon (NASA device, S/N 157, 1200× magnification).



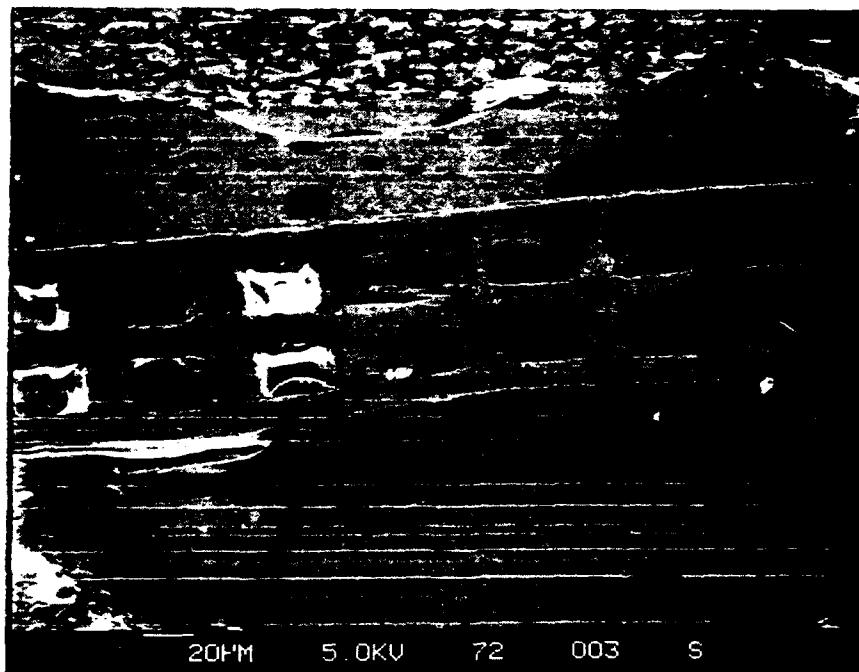


Figure 18a. Note epoxy contamination on die (dark areas) (NASA device, S/N 172, 350× magnification). Ribbon is heavily contaminated. Bright openings in mesh are filled by epoxy, which is charging.

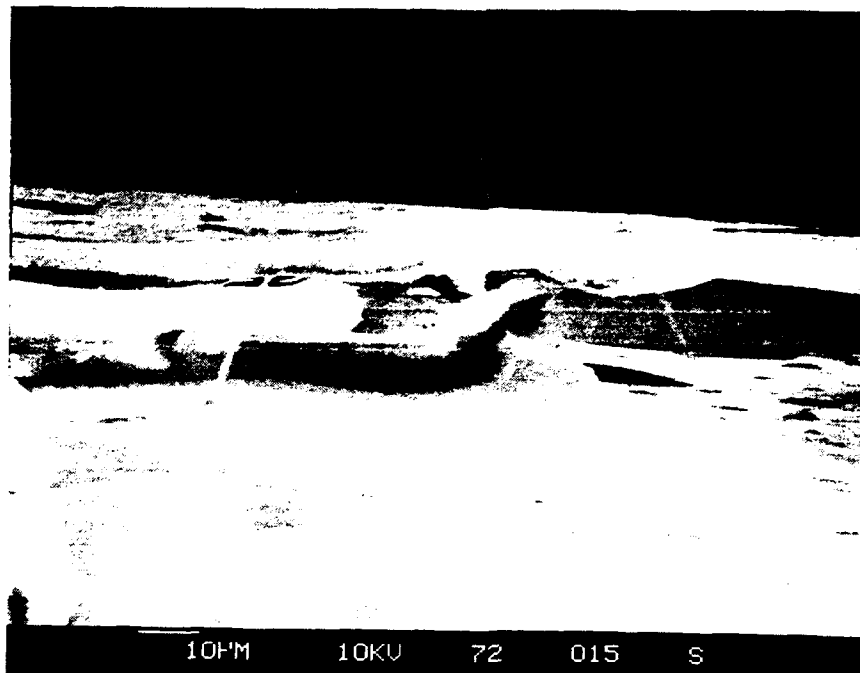


Figure 18b. Mesa is contaminated. Bright regions represent epoxy charging in the SEM (NASA device, S/N 172, 1200× magnification). Note stringers of epoxy from ribbon to die.

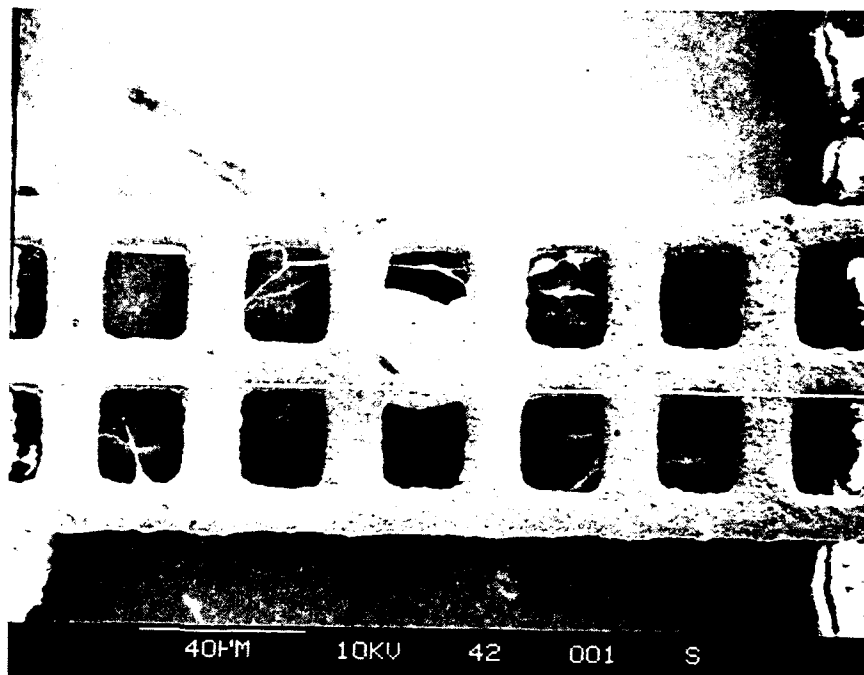


Figure 19a. Stringers of epoxy can be seen in this top view of the ribbon (NASA device, S/N 142, 575× magnification).

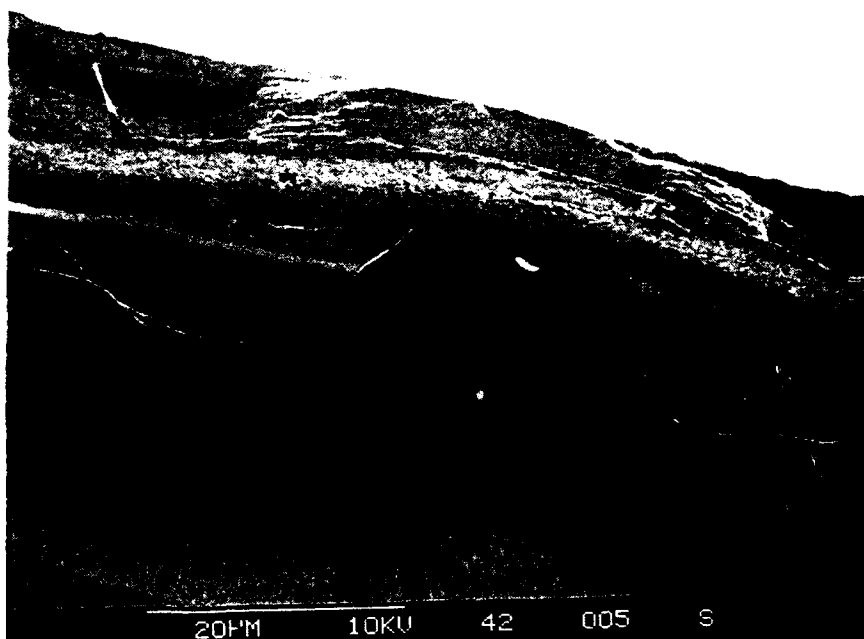


Figure 19b. The mesa of this device is covered by a mound of epoxy (NASA device, S/N 142, 1725× magnification). There is no evidence of a tapering pinnacle.

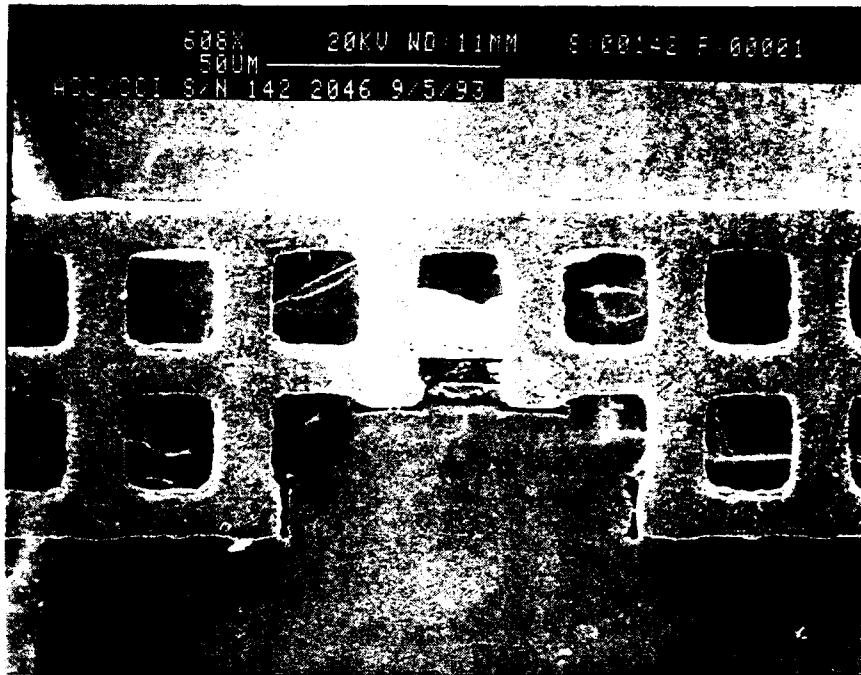


Figure 20a. One side of the ribbon has been cut away by ion milling to better expose the ball-mesa contact (NASA device, S/N 142, 608 $\times$  magnification).



Figure 20b. Mesa region. The Ge has fracture (NASA device, S/N 142, 2000 $\times$  magnification). No "stalk" evident.

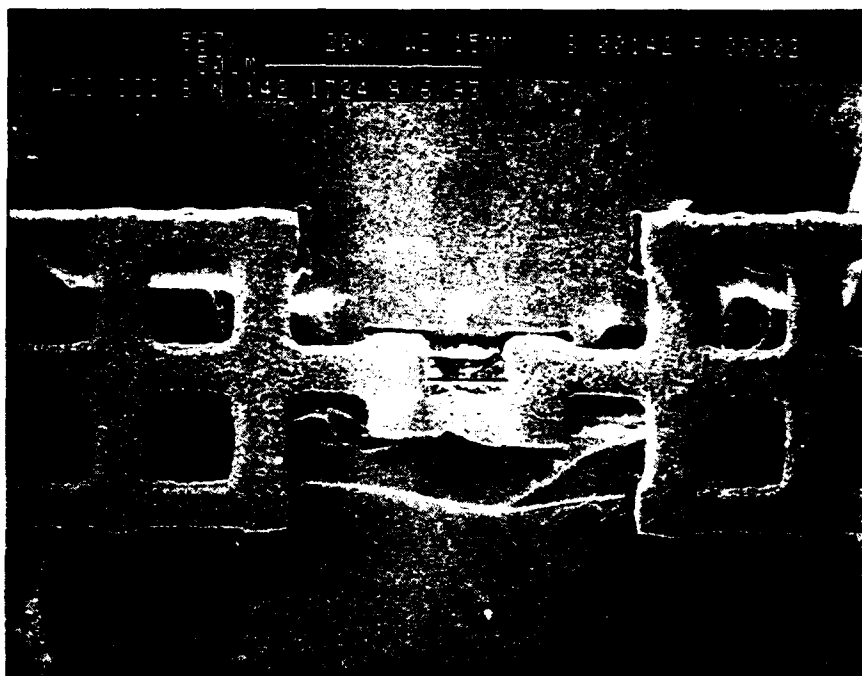


Figure 21a. The other side of the ribbon has been cut away to further expose the contact region (NASA device, S/N 142, 567 $\times$  magnification).

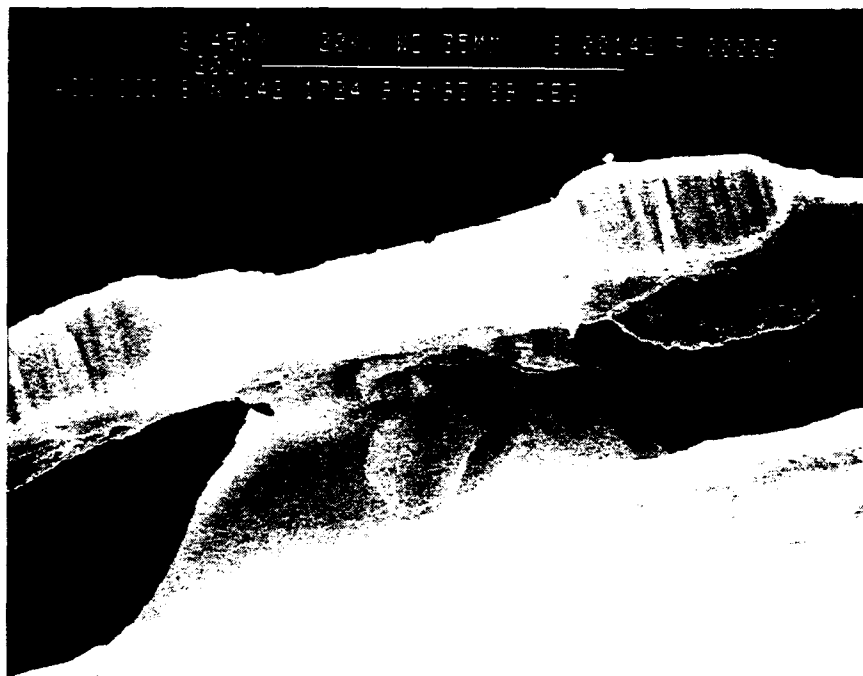


Figure 21b. This is the other side of the "mesa" (see Fig. 20b) (NASA device, S/N 142, 2450 $\times$  magnification). Still no evidence of a "stalk."

#### IV. DISCUSSION AND CONCLUSIONS

The SEM examination of tunnel diodes raised concerns about procedures employed in their fabrication. This information was shared with the contractors during a site visit. Stereoscopic images proved particularly effective in illustrating the features of concern. Previous site visits had already resulted in a substantial improvement of the contractors' process controls, e.g., general cleanliness, elementary precautions against contamination, and monitoring of the purity of the distilled water used in the fabrication. The additional information developed here served to sensitize the contractors further.

The package atmosphere analysis of the NASA diodes revealed values for water vapor, hydrocarbons, and fluorocarbons sufficiently high that comment is warranted. MIL-STD-883 method 1018.2 specifies that the internal package atmosphere should contain less than 5000 ppm by volume of water vapor, and, by this criterion, the devices "failed" the test. According to John Pernicka, the owner of Pernicka Corp., some experimental difficulties were encountered with these particular parts.<sup>7</sup> The mass spectrometer has a dynamic range of about 5 orders of magnitude in pressure, and was set up assuming package gas contents in the ppm range. Because the water content was quite high, the instrument went off scale. A conscious decision was made not to change the instrument settings even after the first device was punctured to ensure consistency in the measurements. Nevertheless, the "bottom line" is that these devices do have a very large moisture content. In Pernicka's opinion, the moisture very likely arises from the epoxy resin in the package. The high hydrocarbon concentration may also arise from improper curing of the epoxy. The high fluorocarbon content could be residual solvent or a residue from gross leak testing, which usually involves immersing the part in fluorocarbon. It should also be pointed out that there are some features of the package construction that might be implicated in the anomalous gas composition values. A grayish, flexible material covers part of the circuit board (Figure 22). No one seems to know anything about the composition or function of this "stuff."

The presence of epoxy-resin contamination in the form of stringers under the contact ribbon and, indeed, not infrequently the complete coating of the mesa by epoxy was the most alarming observation. Epoxy-resin contamination is a serious problem because of the stresses that will arise as a consequence of differential thermal expansion of the germanium mesa, the ball contact, the ribbon, and the epoxy contaminant. These stresses are known to lead to device degradation.<sup>4,5</sup>

In response to the information provided and the recommendations made, new DMSP diodes were fabricated by CCI after the introduction of additional process controls. These new procedures included greater attention to cleanliness and the introduction of inspection steps using optical microscopy. Once workers are made aware of what to look for, optical microscopy can reveal some contamination problems. The new DMSP diodes appear to be much "cleaner," in general. Epoxy contamination is not evident. Better attention to detail and inspection was an essential first step.

Aerospace also recommended that diodes produced for DMSP be subjected to an additional stabilization bake at 100°C for 48 h. After the stabilization bake, diodes are subjected to a biased burn-in at 100°C for 240 h. Finally, the diodes are temperature cycled 10 times between

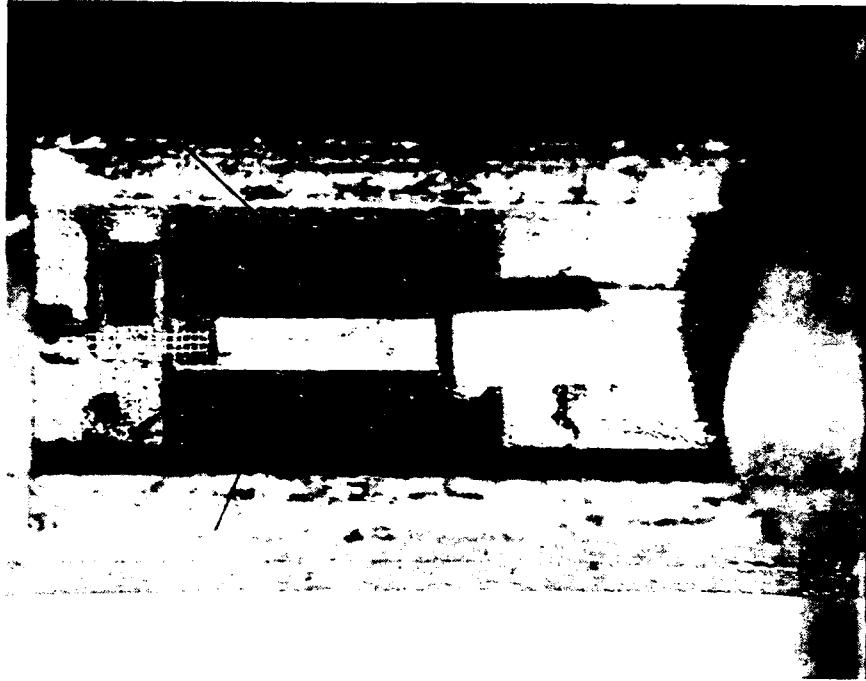


Figure 22. Optical micrograph of a package interior. The arrows point to the grayish, flexible material of unknown function. The diode assembly proper is the rectangular, lighter structure just to the right of center (NASA device, S/N 136, 14× magnification).

-65°C and 100°C. Diodes exhibiting a change in peak-to-valley ratio greater than 10% are rejected. The Aerospace screen has been proven very effective in removing devices at risk of early failure.

The process improvements and thermal-cycling screen have resulted in much more reliable DMSP detectors. Much less confidence can be placed in the reliability of the NASA devices. The NASA tunnel diodes were fabricated before the additional process controls developed for DMSP were implemented and were not subjected to the new thermal screen. The severe contamination by excess epoxy resin in the mesa region and under the ribbon on these devices is completely consistent with observations made of the older DMSP components. The NASA devices may be said to be "in family." Diode failures as a consequence of stress built in during fabrication definitely cannot be ruled out.

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- <sup>2</sup> S. M. Sze, *Physics of Semiconductor Devices*, John Wiley and Sons, New York (1981)
- <sup>3</sup> A. G. Revesz and P. L. Fleming, "Tunnel Diodes in Satellite Communications," *Comsat Technical Review* **3**, 257-271 (1978).
- <sup>4</sup> A. G. Revesz, J. Reynolds and J. Lindmayer, "New Aspects of Failure Mechanism in germanium tunnel diodes," *Solid State Electronics* **14**, 1137-1147 (1971).
- <sup>5</sup> P. L. Fleming, "Prescreening techniques for flight germanium tunnel diodes," *Comsat Technical Review* **4**, 449-460 (1974).
- <sup>6</sup> J. Orloff, "High resolution focused ion beams," *Rev. Sci. Instrum.* **64**, 1105-1130 (1993).
- <sup>7</sup> Telephone conversation, G. W. Stupian and J. C. Pernicka ( July 21, 1993).

## APPENDIX — PRINCIPLES OF TUNNEL DIODE OPERATION

Consider a junction in which both the p and n regions are so heavily doped that the semiconductor on both sides of the junction is degenerate, i.e., the charge carriers are governed by quantum mechanical rather than classical rules. The energy-band diagram of such a junction, at thermal equilibrium, is shown in Figure A1. The Fermi level lies in the conduction band in the n-type semiconductor and within the valence band in the p-type semiconductor. In order for current to flow, filled states on one side of the junction must be aligned with empty states across the junction. At thermal equilibrium, the Fermi level is constant across the junction. There are no filled states above the Fermi level on either side of the junction, and there are also no empty states below the Fermi level on either side. As the junction is biased in the forward direction, the filled conduction-band states are raised in energy and begin to overlap the empty states in the valence band. Current begins to flow as the electrons cross the depletion region by quantum mechanical tunneling (whence the name "tunnel diode"). As the bias voltage increases further, the current reaches a maximum as the filled and empty states attain the optimum energy alignment. With further increase in bias voltage, the filled states rise above the acceptor states, and the current decreases. The current, therefore, goes through a maximum with increasing voltage, and the tunnel diode has a region of "negative" resistance. The varying amount of band overlap responsible for the characteristic current-voltage behavior of tunnel diodes is illustrated schematically in Figure A2. The current does not go to zero as the voltage is raised still further because the normal thermal current flows across the decreasing potential barrier.

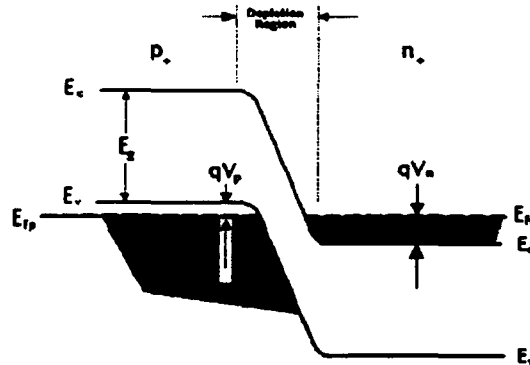


Figure A1. Band structure of a  $p^+ - n^+$  junction.



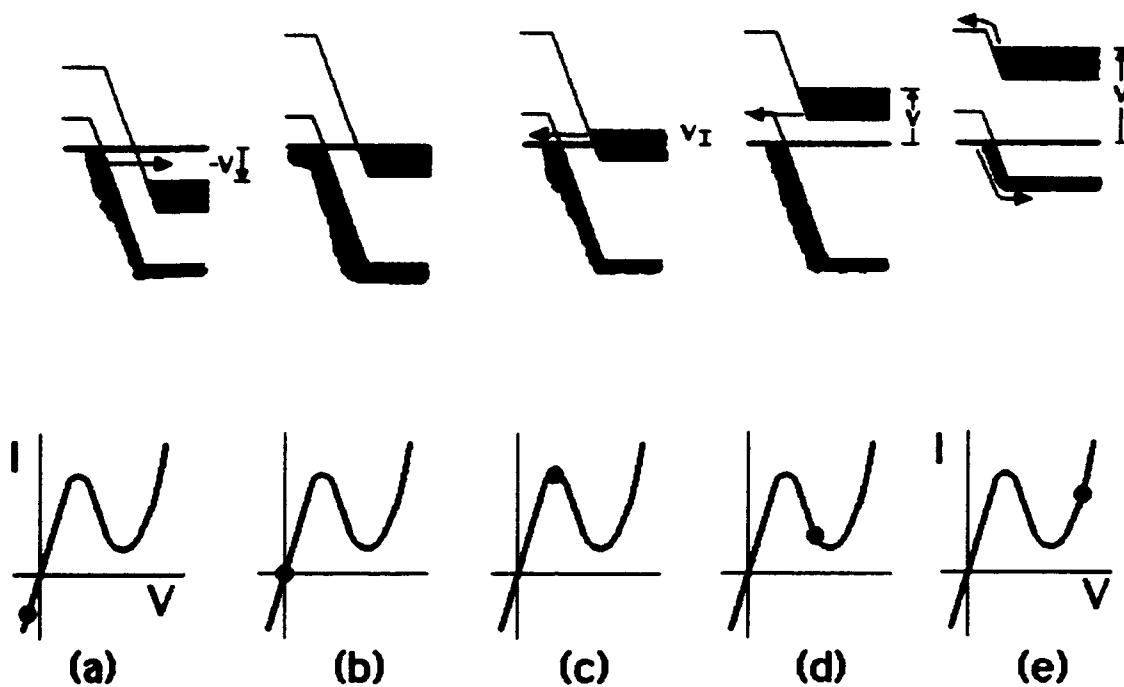


Figure A2. Tunnel diode energy band diagrams at (a) reverse bias, (b) thermal equilibrium (zero bias), (c) as valley current is approached, and (e) as thermal current flows (from Ref. 2).